



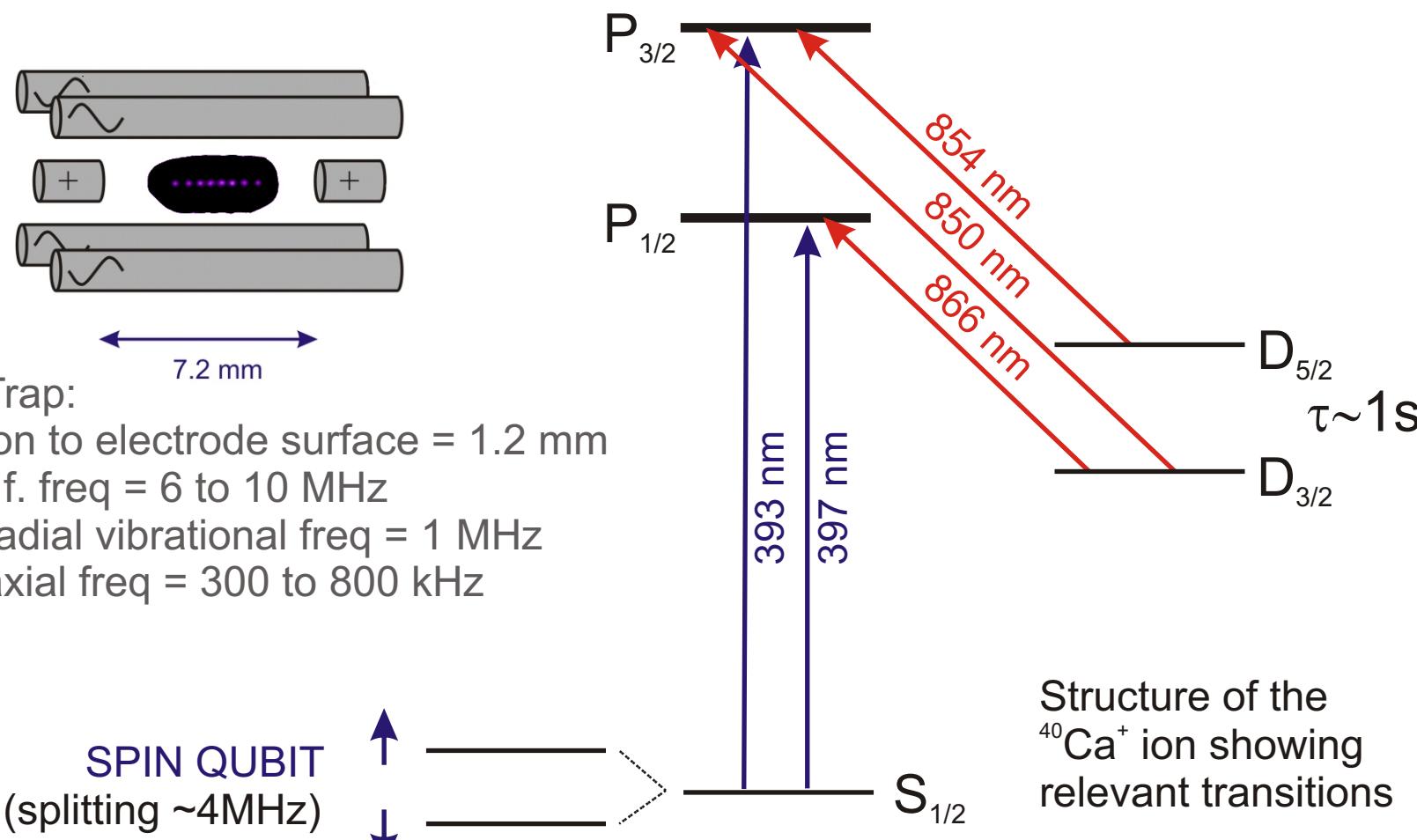
Long-lived coherence in $^{43}\text{Ca}^+$ and $^{40}\text{Ca}^+$ trapped-ion qubits

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$^{40}\text{Ca}^+$ qubits

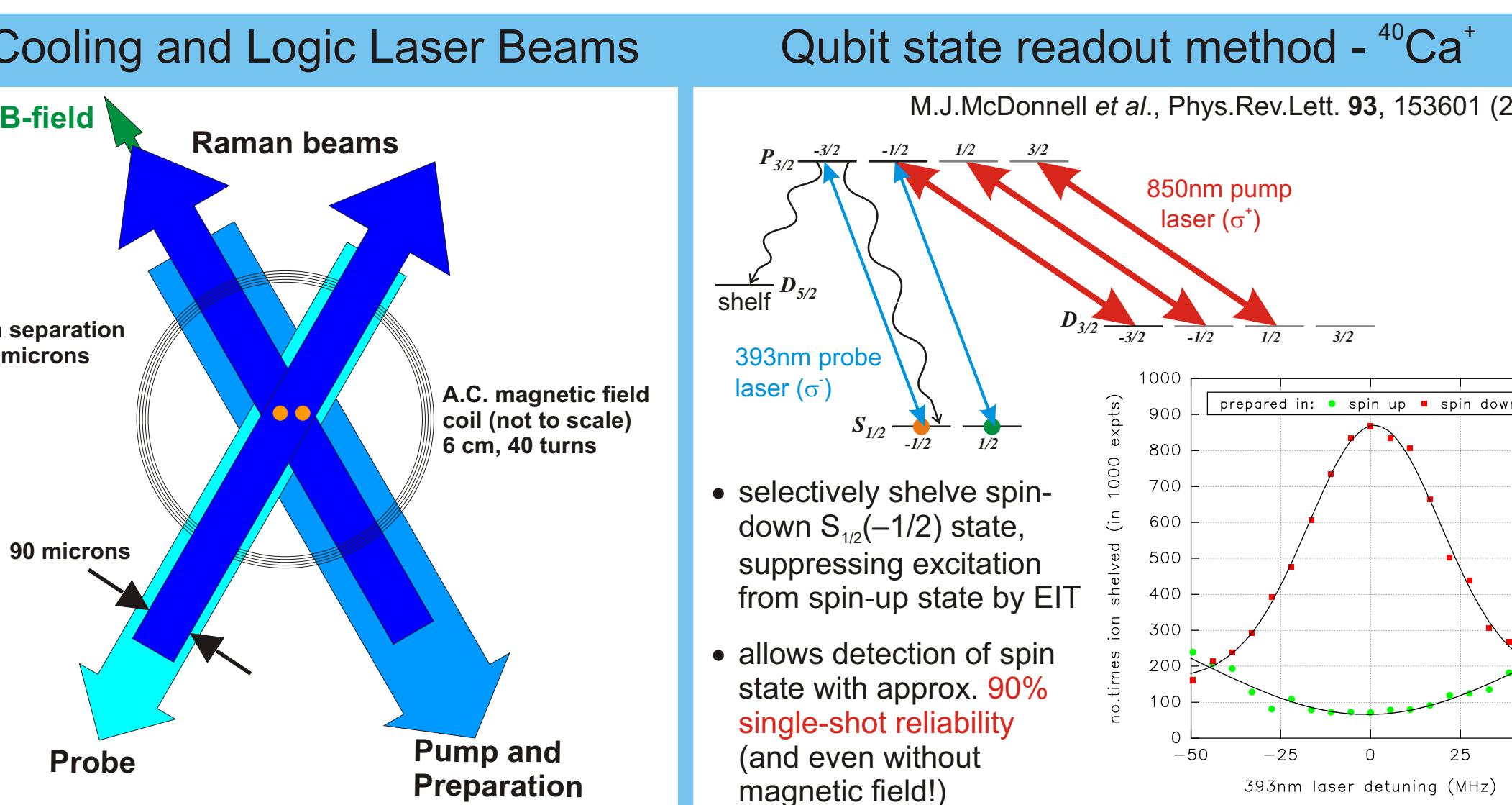
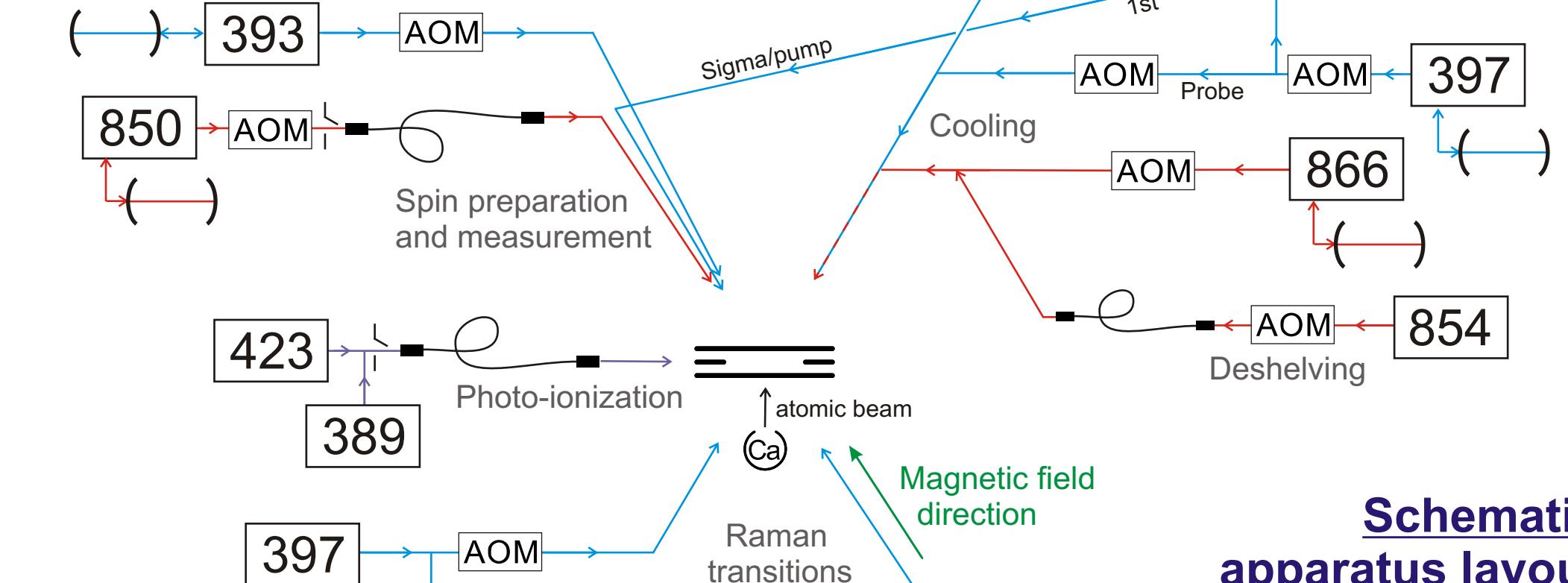
Long coherence times are essential for implementing quantum information processing. We use $^{40}\text{Ca}^+$ spin-qubits to investigate the coherence of motional states (used in an ion trap for qubit-qubit coupling) and, below, we measure coherence times of $^{43}\text{Ca}^+$ hyperfine qubits.



Experimental studies:

- cooling of a single ion to ground state in one dimension by three varieties of Raman sideband cooling, $\langle n \rangle = 0.02$
- cooling of both axial modes of an ion pair close to ground state
- motional heating rate <2 phonon/sec (best), <10 phonon/s (typical)
- motional coherence time $\sim 200\text{ms}$ (between $n=0$ and $n=1$ states)
- magnetic field independent qubit ($^{43}\text{Ca}^+$) coherence time $0.9(2)\text{sec}$

Experimental details



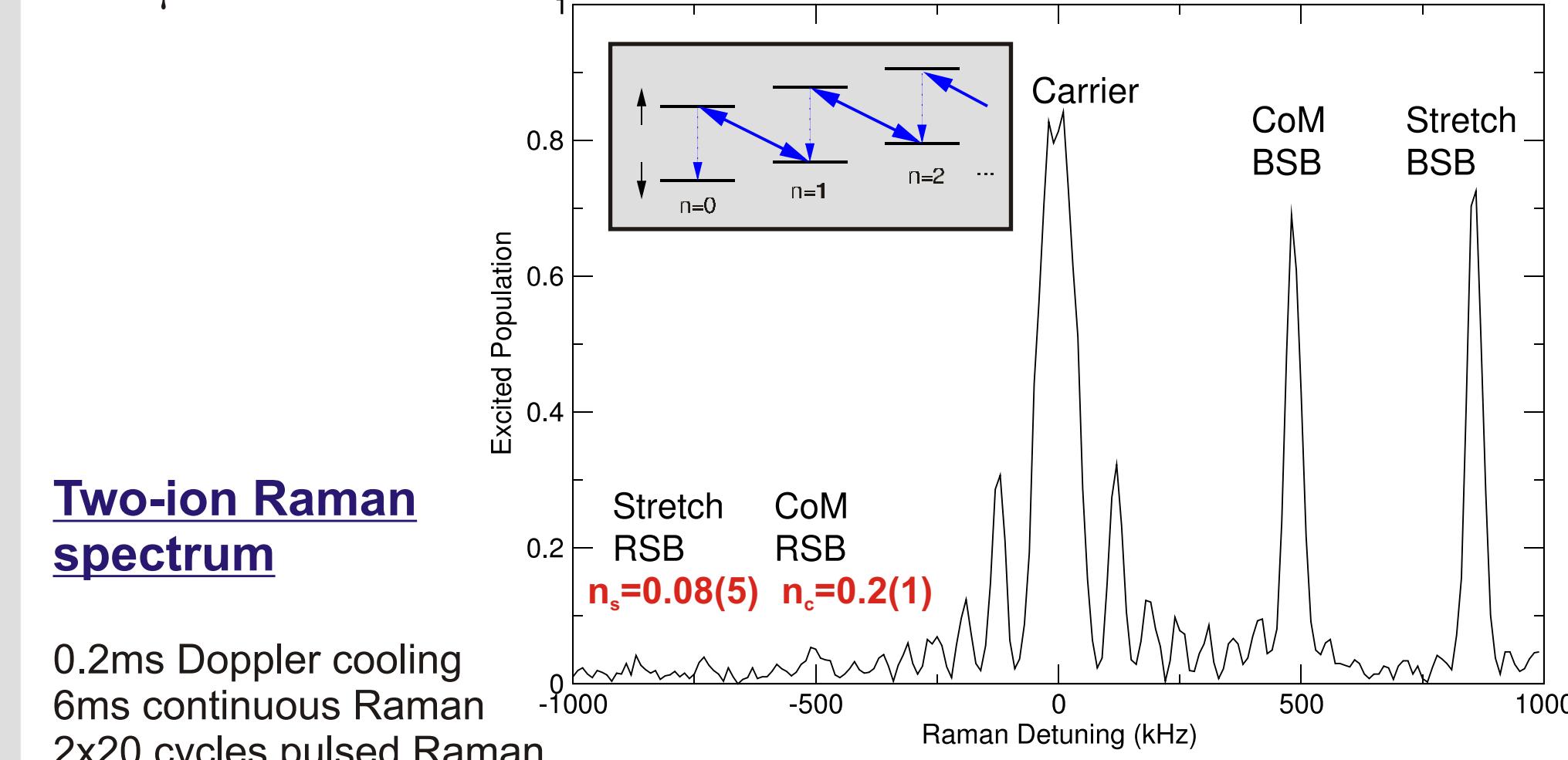
Ground state cooling

The motional state of the string of ions acts as an extra degree of freedom that can be used to couple the ions together coherently. In order to use the modes of vibration of the ion strings as a quantum "bus" the ions must be cooled to the ground state of the trapping potential. Cooling is performed in three stages:

- Doppler cooling $\rightarrow 500\mu\text{K}$
- Continuous Raman sideband cooling $\rightarrow \langle n \rangle \approx 1$
- Pulsed Raman sideband cooling $\rightarrow \langle n \rangle \approx 0$

The final ion temperature can be obtained from the ratio of the red sideband (RSB) height to the blue sideband (BSB) height for a given mode of vibration.

For a single ion, we achieve $\langle n \rangle = 0.02(1)$, in an 820kHz trap, giving $T = 10\mu\text{K}$.

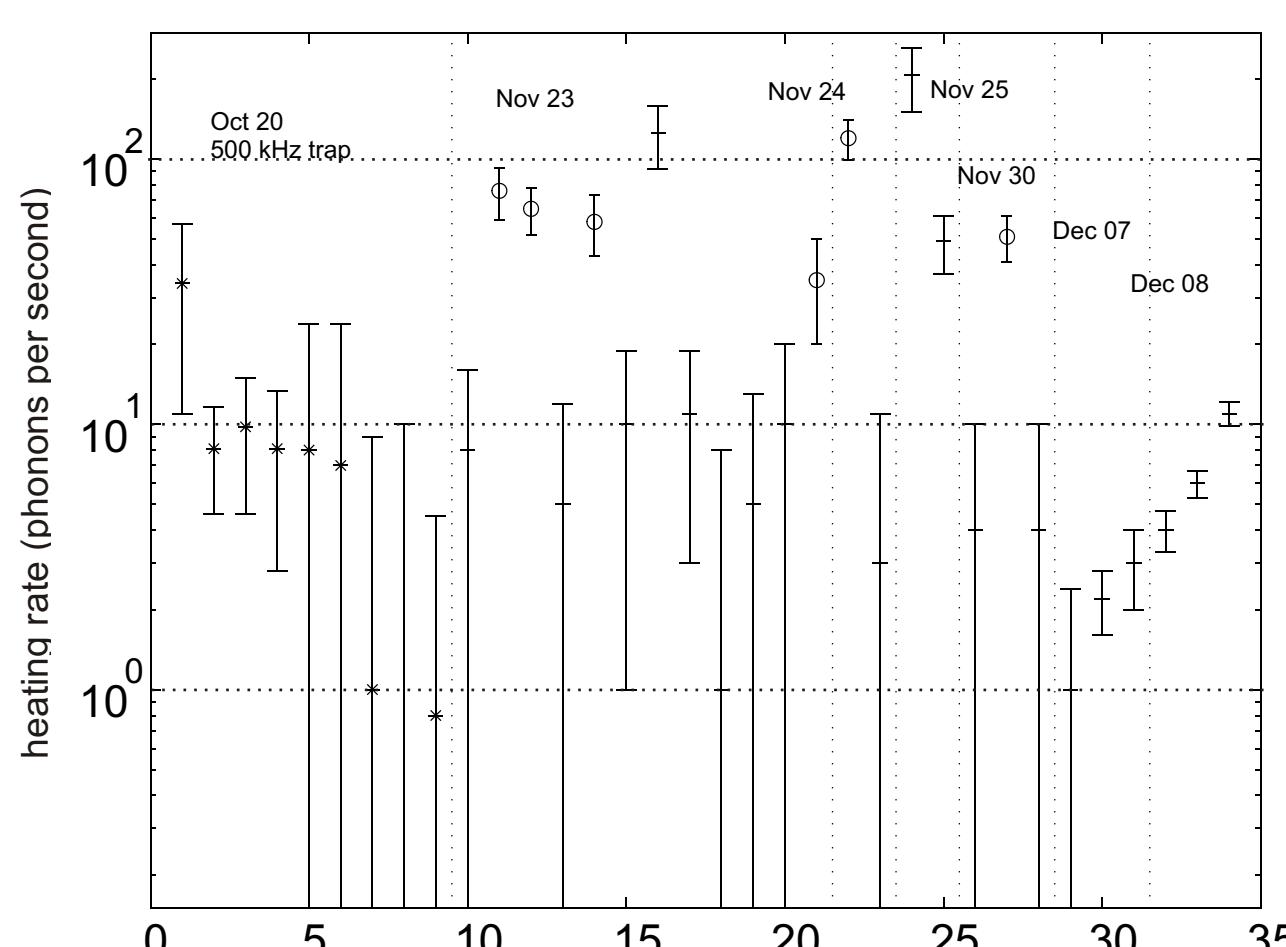


Long-lived motional coherence

Single-ion heating rate measurements

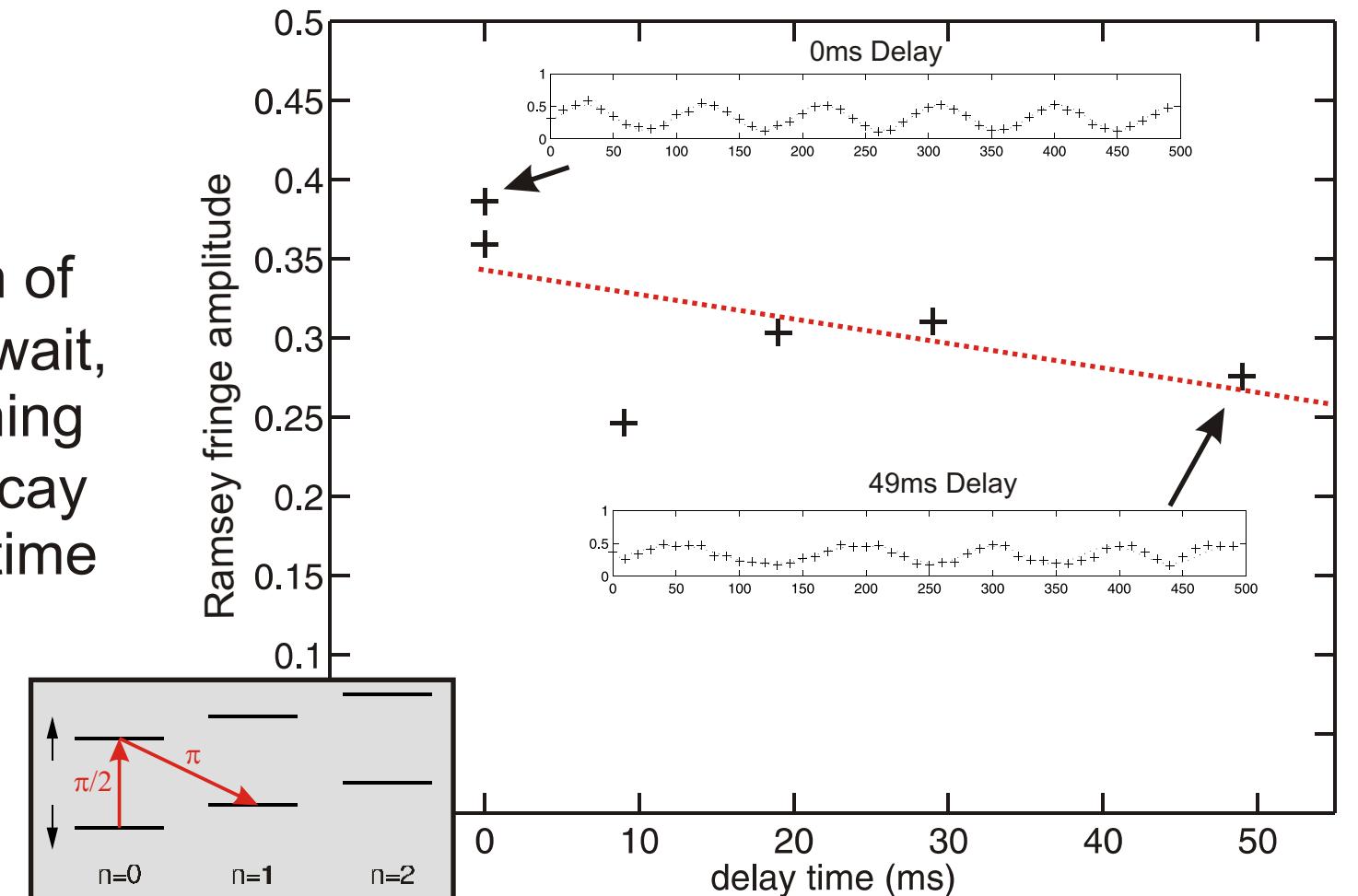
Method: cool to the ground state, wait 10-50ms, measure temperature by sideband strengths.
 Circled points: with weak laser heating

Results: <2 phonon/sec (best)
 <10 phonon/sec (typical)
 (but occasionally anomalously high!)



Motional decoherence

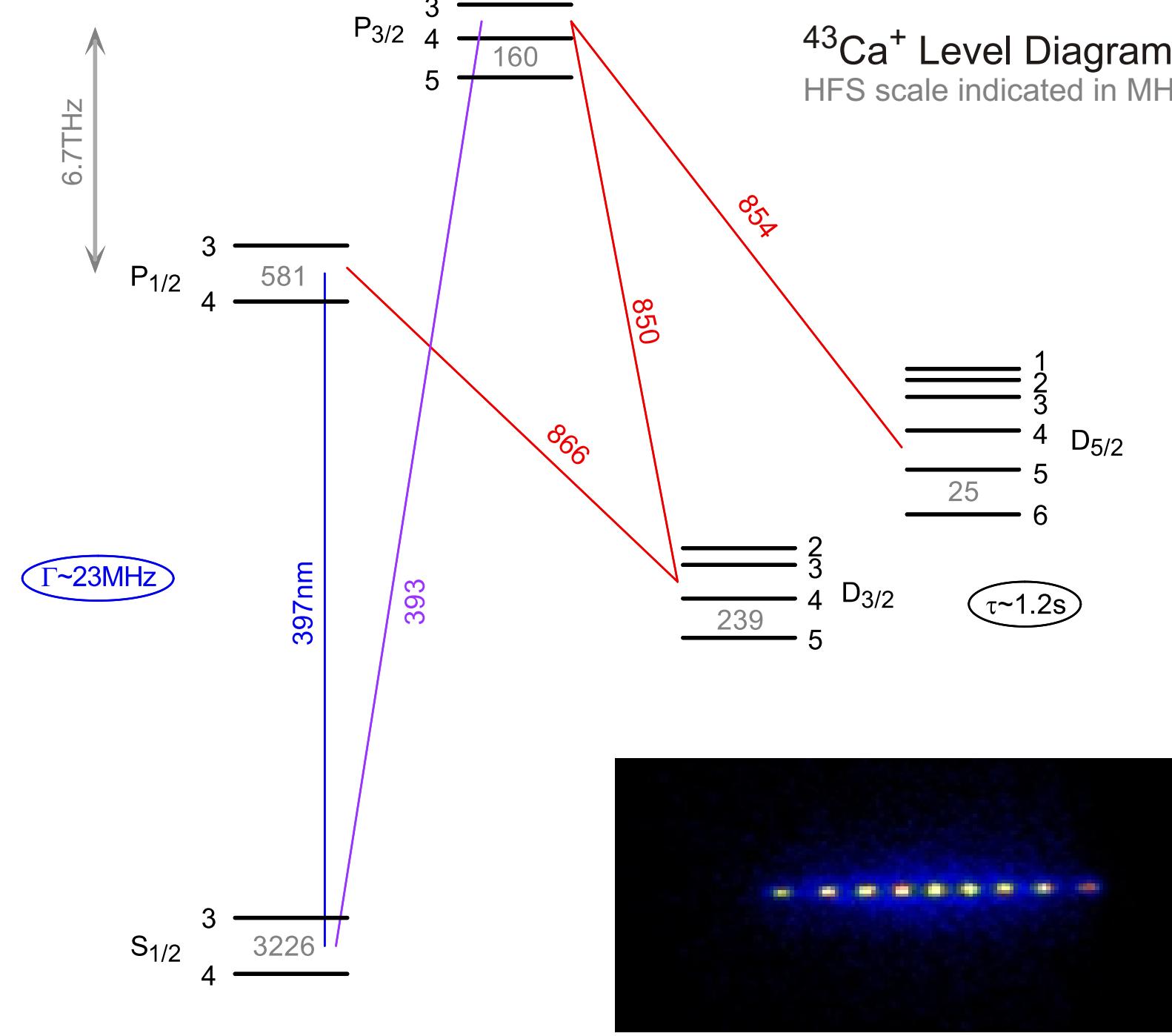
A "Ramsey" experiment on the motional state:
 carrier $\pi/2$, RSB $\pi \rightarrow$ superposition of $(\downarrow, n=0) + (\downarrow, n=1)$ vibrational levels, wait, undo the superposition while scanning the phase of the final $\pi/2$ pulse. Decay of fringe contrast gives coherence time of $\sim 200\text{ms}$.



$^{43}\text{Ca}^+$ qubits

The $^{43}\text{Ca}^+$ isotope offers several advantages over $^{40}\text{Ca}^+$:

- easier qubit read-out due to 3.2GHz ground state hyperfine structure splitting
- qubit states which are independent of magnetic field to first order, at both low field and moderate ($\sim 150\text{G}$) field

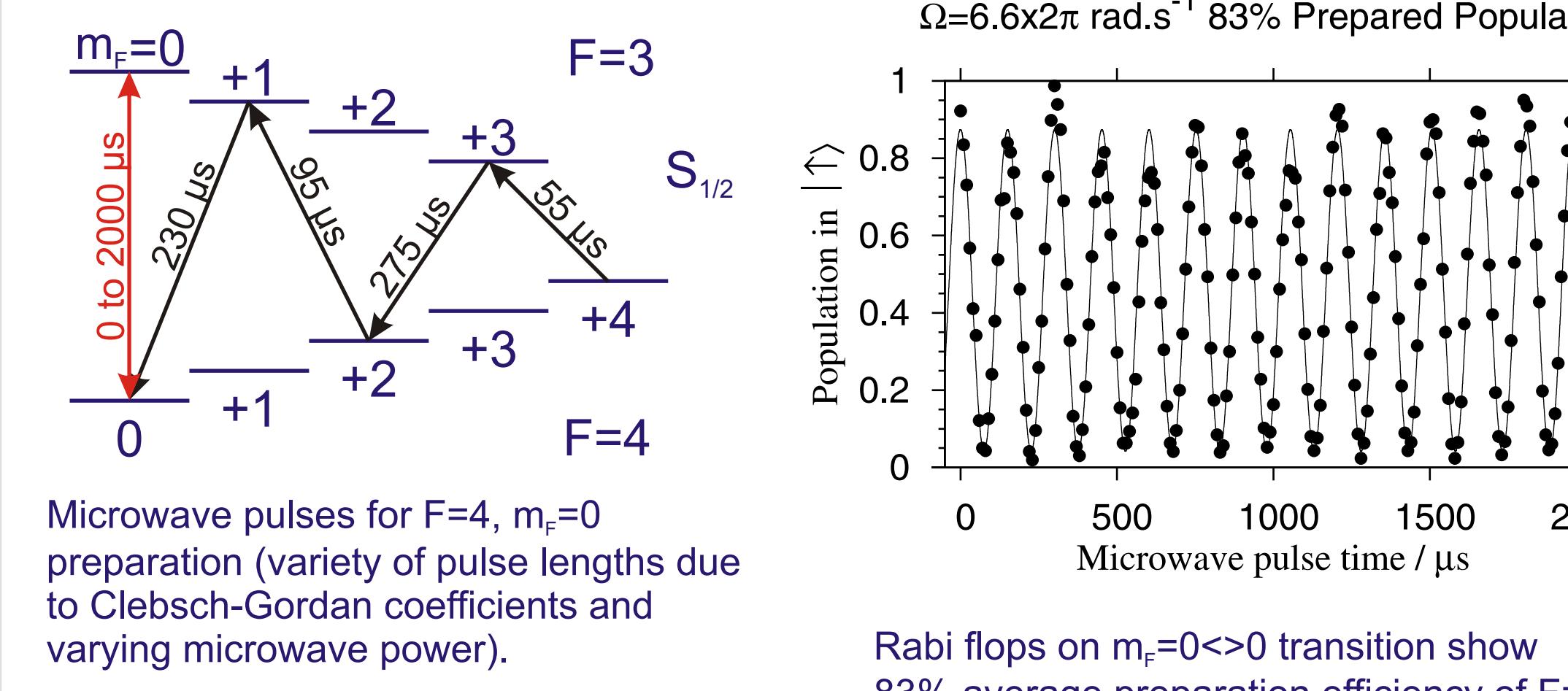


Above: pure crystals of $^{43}\text{Ca}^+$ can be loaded from a natural abundance (0.14%) source by isotope-selective photo-ionization

Experimental details

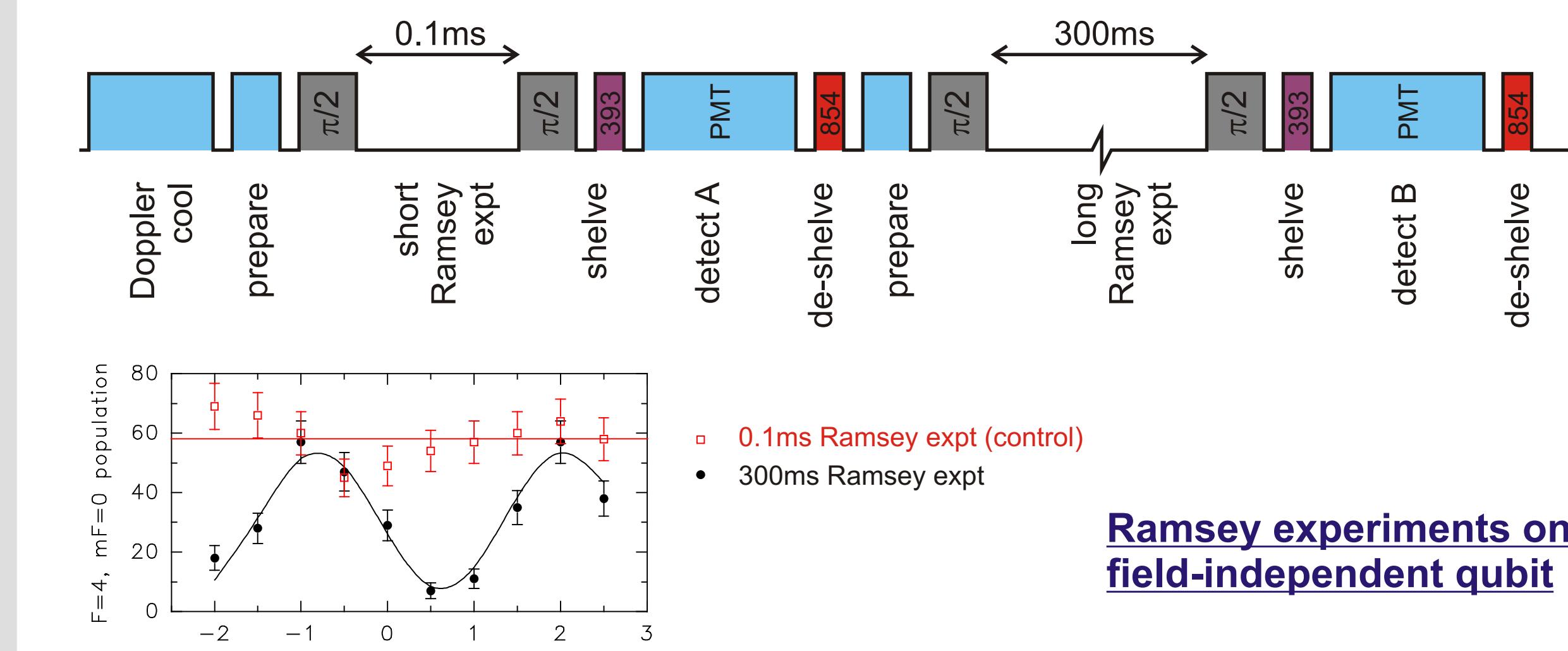
Same apparatus as $^{40}\text{Ca}^+$, above, but:

- 3.2GHz EOM on 397nm beam drives $F=3>4$ and $F=4>4$ transitions
- can prepare $F=4, m_F=+4$ "stretched" qubit state with $\sim 100\%$ efficiency, by optical pumping with σ^+ polarized 397nm beams
- can prepare $F=3, m_F=0$ field-independent "clock" qubit state with $\sim 15\%$ efficiency, by switching off EOM (no σ polarized beam available)
- can prepare $F=4, m_F=0$ clock state with up to 90% efficiency, by applying a sequence of microwave π pulses to the $F=4, m_F=+4$ state (see below)
- shelving readout with $\sim 95\%$ efficiency, by single pulse of 393nm laser on $F=4>5$ (no 850nm laser needed)
- 3.2GHz microwaves used for coherent state manipulation



Long-lived internal coherence

We can observe many (~ 270) Rabi flops on the $m_F=0$ field-independent transition, lasting $>30\text{ms}$ (see plot at bottom of poster). However, this time-scale may be limited by microwave power stability, so we perform a Ramsey experiment to measure the qubit coherence time. To check for, e.g. drift of readout efficiency, we interleave a short Ramsey experiment (0.1ms gap) with a long Ramsey experiment (up to 300ms gap). Since the microwave frequency is swept over only a few Hz, the short Ramsey experiment is essentially a π pulse.



Varying the long Ramsey delay (right), we find an internal state coherence time of $T_2 = 0.9(2)\text{sec}$.

At working field of 1.7G , residual field-sensitivity is $\sim 4\text{Hz/mG}$. The reduction in fringe contrast is consistent with field drifts at the level of 0.1mG/hr .

Simulations

The energy levels of $^{43}\text{Ca}^+$, and transitions between them, were simulated in MATLAB using a rate equations technique. The model includes the 4S, 4P and 3D terms (144 levels), and all the (optical frequency) electric dipole transitions.

COOLING

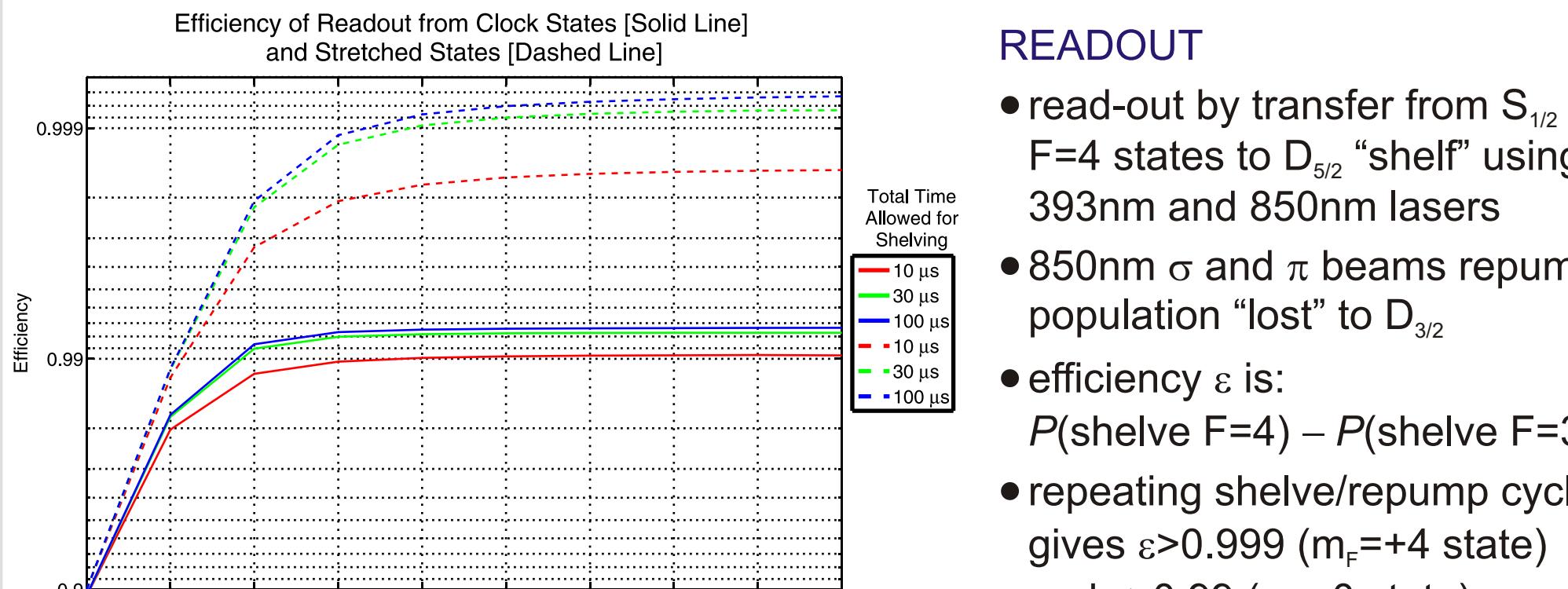
- Doppler cooling with 397nm and 866nm lasers
- 3.2GHz sidebands on 397nm laser repump HFS
- 170MHz sidebands on 866nm laser improve fluorescence
- comparison with $^{40}\text{Ca}^+$ shows higher laser intensities are needed for given fluorescence

PREPARATION

- prepare $F=4, m_F=0$ using σ polarized 397nm beams tuned to $F=3>4$ and $4>4$
- desired state is dark, but off-resonant $F=4>3$ transitions limit efficiency to 98.9%
- prepare $F=4, m_F=+4$ with σ^+ polarized beams, efficiency only limited by σ^+ purity

READOUT

- read-out by transfer from $S_{1/2}$ $F=4$ states to $D_{3/2}$ "shelf" using 393nm and 850nm lasers
- 850nm σ and π beams repump population "lost" to $D_{3/2}$
- efficiency ε is: $\varepsilon = P(\text{shelf } F=4) - P(\text{shelf } F=3)$
- repeating shelf/repump cycle gives $\varepsilon > 0.999$ ($m_F=+4$ state) and $\varepsilon > 0.99$ ($m_F=0$ state)



Rabi-flopping on field-independent $^{43}\text{Ca}^+$ qubit (~ 270 flops)

